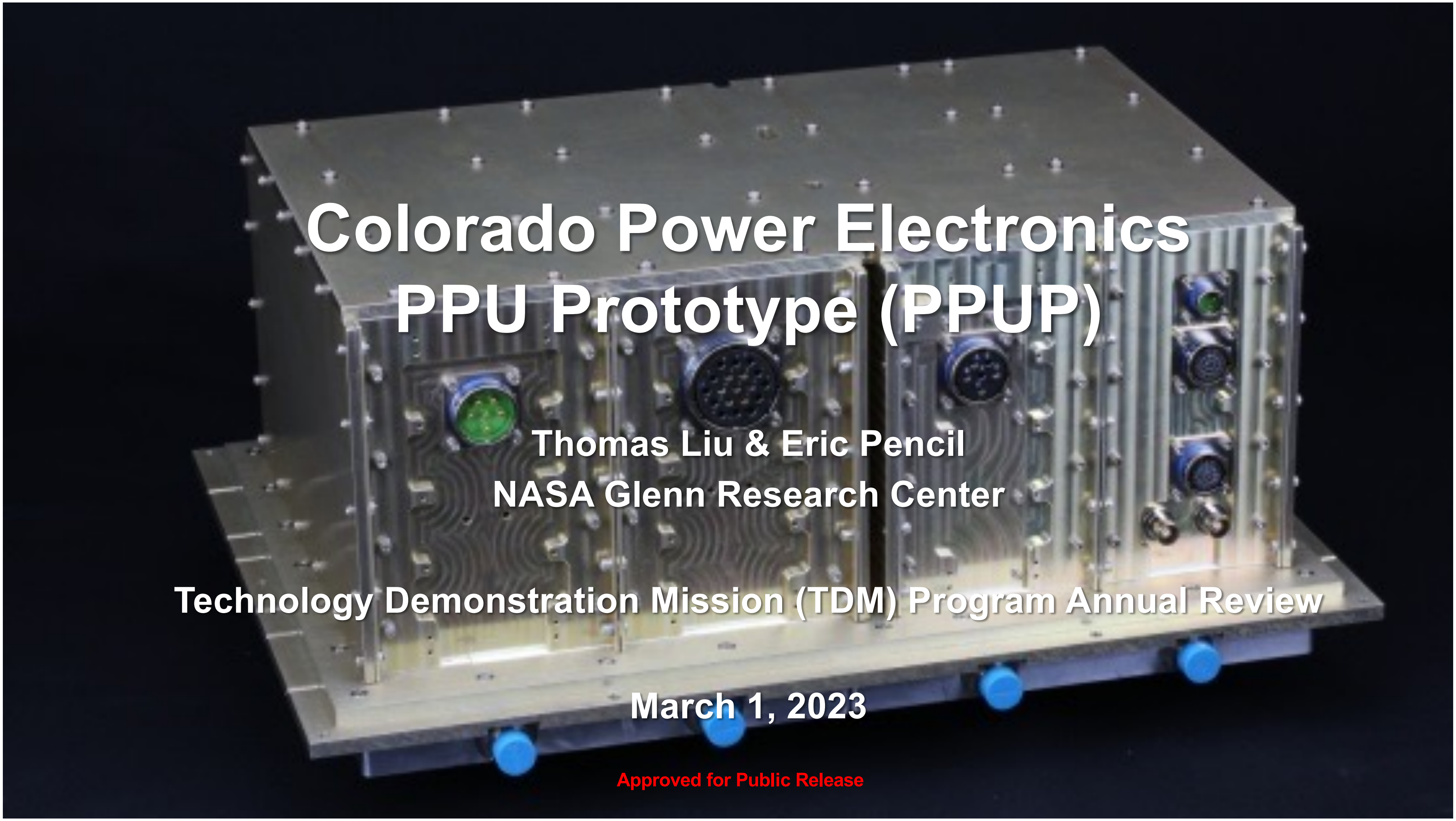

Colorado Power Electronics PPU Prototype (PPUP)

Thomas Liu & Eric Pencil

NASA Glenn Research Center

Technology Demonstration Mission (TDM) Program Annual Review

March 1, 2023

Project Contributors

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- **Colorado Power Electronics**
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  - Kevin O'Connor
  - Daniel Powell
  - Vlad Shilo

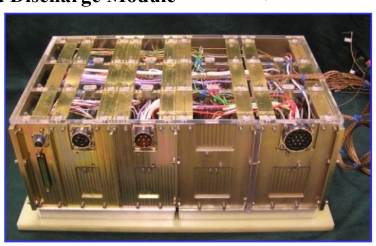
CPE-NASA Public-Private Partnership (1/2)

- Since 2003, NASA has awarded Colorado Power Electronics (CPE) 11 SBIR (Small Business Innovation Research) grants to develop and mature power processing unit (PPU) technologies for a variety of electric propulsion (EP) needs.

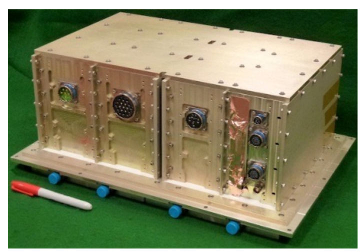
- In 2005, CPE began work on a high-performance PPU architecture that would support missions utilizing a variety of NASA and commercial Hall-effect thrusters (HET) in the popular 5-kW power class, including the NASA HiVHAc (High-Voltage Hall Accelerator).

1-kW Breadboard Discharge Module

1st application of full-resonant power converter to kW-class EP



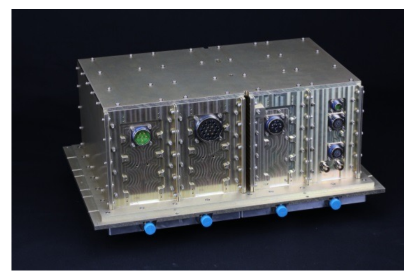
Brassboard PPU #1



Brassboard PPU #2

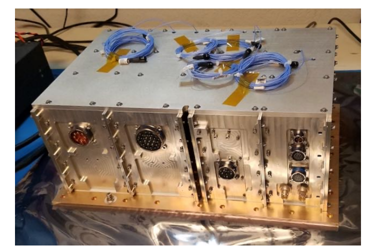
Tested for >1,000 hr in vacuum environment at GRC

Performance characterized at GRC in thermal-vacuum tests with integrated demonstrations using HiVHAc and Maxar SPT-140



Engineering Model (EM) PPU

Mechanical, thermal, radiation, worst-case, and reliability analyses completed



PDU PPU

Approved for Public Release

CPE-NASA Public-Private Partnership (2/2)

- Via a SBIR Phase III effort with NASA GRC and JPL, CPE has delivered a high-fidelity, flight-like Prototype Development Unit (PDU) PPU to NASA.
- At GRC, the PDU PPU underwent functional / performance checkouts, integrated system tests (IST), and limited* qualification-level environmental testing (i.e., electromagnetic interference / compatibility and thermal-vacuum) to verify that the CPE design meets anticipated NASA mission requirements.
  - *Vibration / pyroshock tests were deferred.

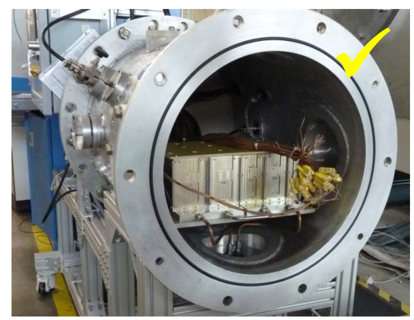
PPUP (ACO)

Benchtop Checkouts & Integrated System Test (IST) #1 in VF-11 ✓

SBIR Phase III

Electromagnetic Interference Lab

Structural Dynamics Lab



VF-70 thermal-vacuum chamber

PPUP (ACO)

IST #2 in VF-11 ✓

ACO Objectives (1/3)

The ACO (Announcement of Collaborative Opportunity) effort will utilize GRC EP test facilities to:

1. Verify CPE PDU PPU integrated performance when operated as part of a complete HET system

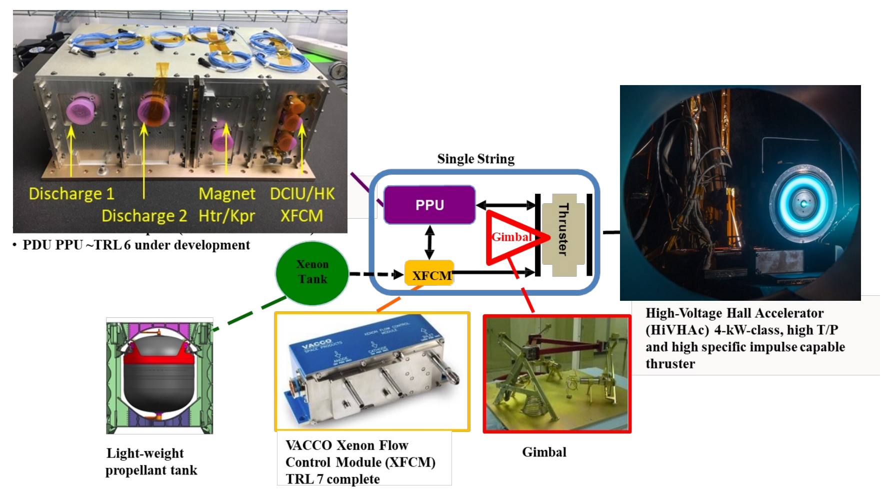
2. Demonstrate CPE PPU compatibility with thrusters from NASA and prospective commercial customers

3. Advance the CPE HET PPU technology readiness level (TRL) to TRL 5+ to encourage mission infusion

4. Provide CPE with PDU PPU performance data and operational lessons learned to refine technology's commercialization plan and to showcase the technology to prospective NASA and commercial end-users

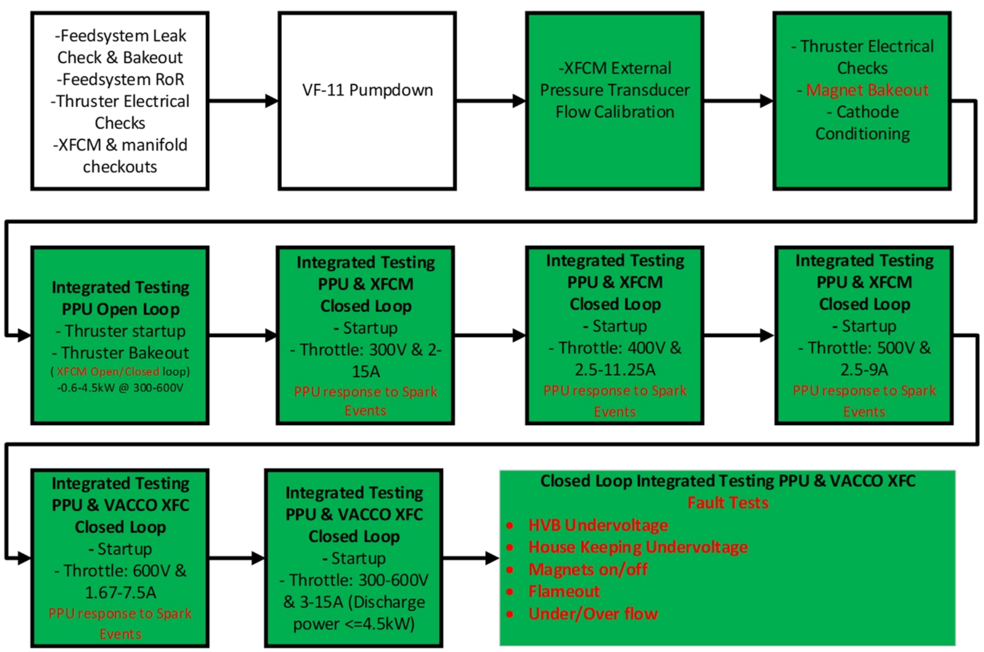
Key Mission Benefits Anticipated

- ❖ High performance and flexible compatibility with different spacecraft buses and thrusters
- ❖ Wide operating range to accommodate deep thruster throttleability for closing more missions
- ❖ Modular, light-weight (low kg/kW) design to facilitate high-power electric propulsion systems
- ❖ Comprehensive PPU design without need for additional subsystem development

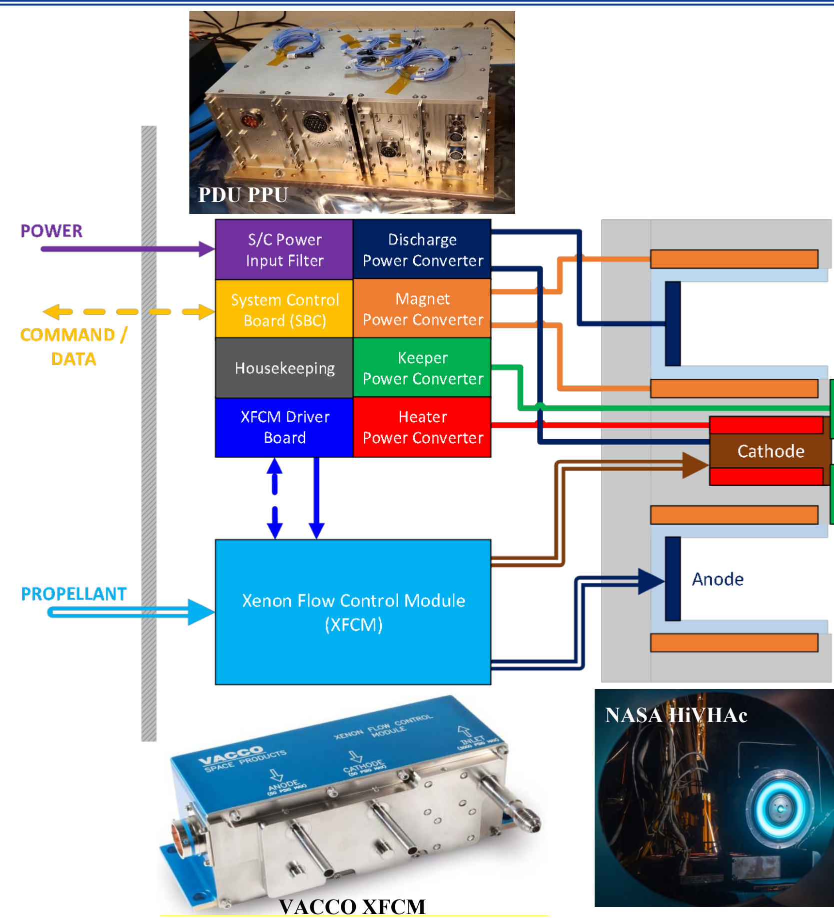


ACO Objectives (2/3)

☑ **Verify CPE PDU PPU integrated performance when operated as part of a complete HET system**

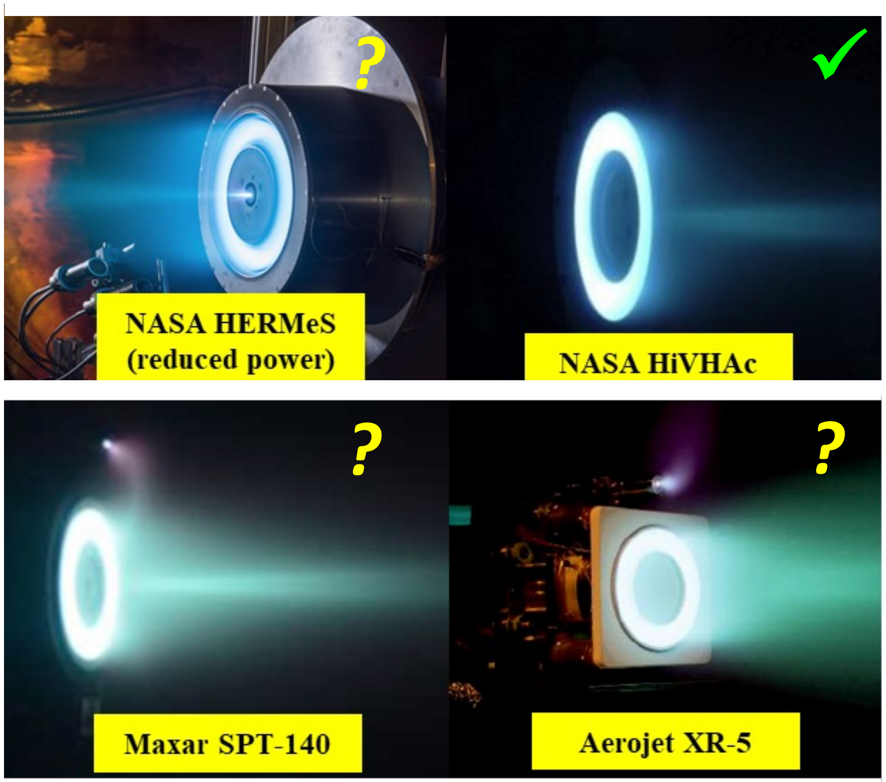


General IST Test Flow

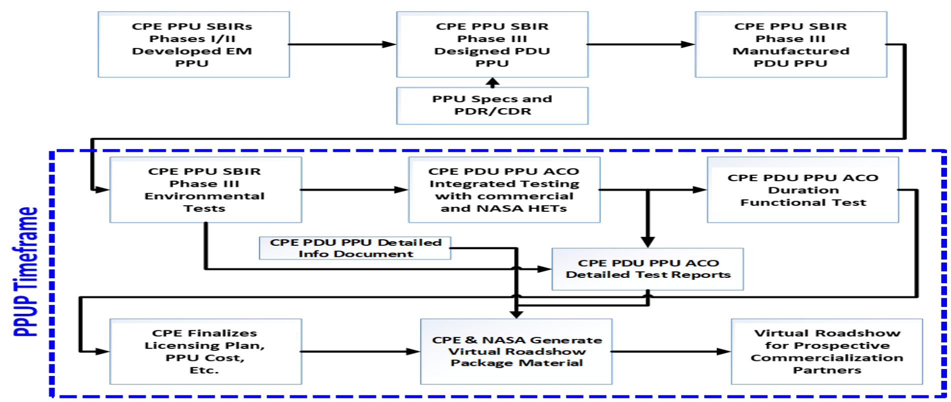


ACO Objectives (3/3)

- ☑ Demonstrate CPE PPU compatibility with thrusters from NASA and prospective commercial customers



- ☑ Advance the CPE HET PPU technology readiness level (TRL) to TRL 5+ to encourage mission infusion
- ☑ Provide CPE with PDU PPU performance data and operational lessons learned to refine technology's commercialization plan and to showcase the technology to prospective NASA and commercial end-users



CPE PPU Commercialization Roadmap (2021)

Project Milestones

NASA GRC		
XFCM flow calibration curves		
Integrated test with EM PPU with upgraded DCIU algorithms	*	Replaced w/ PDU PPU IST #1
Functional and integrated test of PDU PPU with HiVHAc+		
Radiated EMI test of PDU with HiVHAc+ thruster	*	Replaced w/ SBIR EMI/EMC test
Integrated test of PDU with commercial Hall thrusters	*	Thrusters not available
Extended duration integrated test of PDU with HiVHAc+	*	May 2022 TDM PCB descope
Colorado Power Electronics		
Update EM PPU DCIU algorithms		
Deliver PDU PPU to NASA GRC		
Functional and environmental test of PDU	*	Deferred dynamics; partial thermal
Install memory modules in PDU PPU		
Update PDU DCIU firmware		

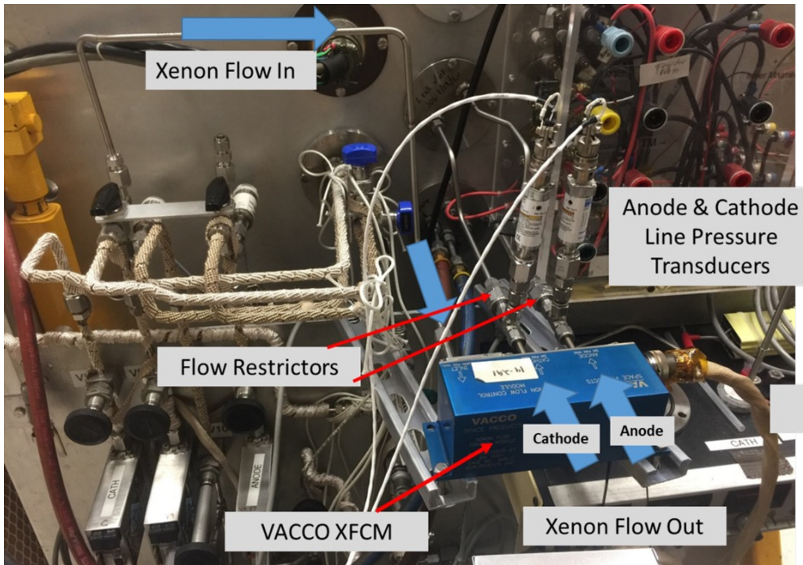
* **COVID-impacted**: ~7-month delay in PDU PPU assembly + ~11-month delay in GRC test activities

CPE-NASA PPUP

Pre-PDU PPU Delivery

VACCO XFCM Calibration & Control Algorithms

- ✓ Determined VACCO XFCM's flow rate relations to feed pressure and temperature (GRC)
- ✓ Implemented relations as PDU PPU control algorithms (CPE)



VACCO XFCM calibration test at GRC VF-8

PDU PPU Assembly (CPE)

- ✓ Designed the PPU, performed all parts selection, and procured all components
- ✓ Sub-contracted flight-certified contractor (DBM Technologies) to assemble the PPU in accordance with IPC-A-610 standards
- ✓ Performed functional testing of PDU PPU prior to GRC delivery in September 2021

PDU PPU sub-assembly functional testing at CPE

Benchtop Functional / Acceptance Testing (1/2)

Test Objectives

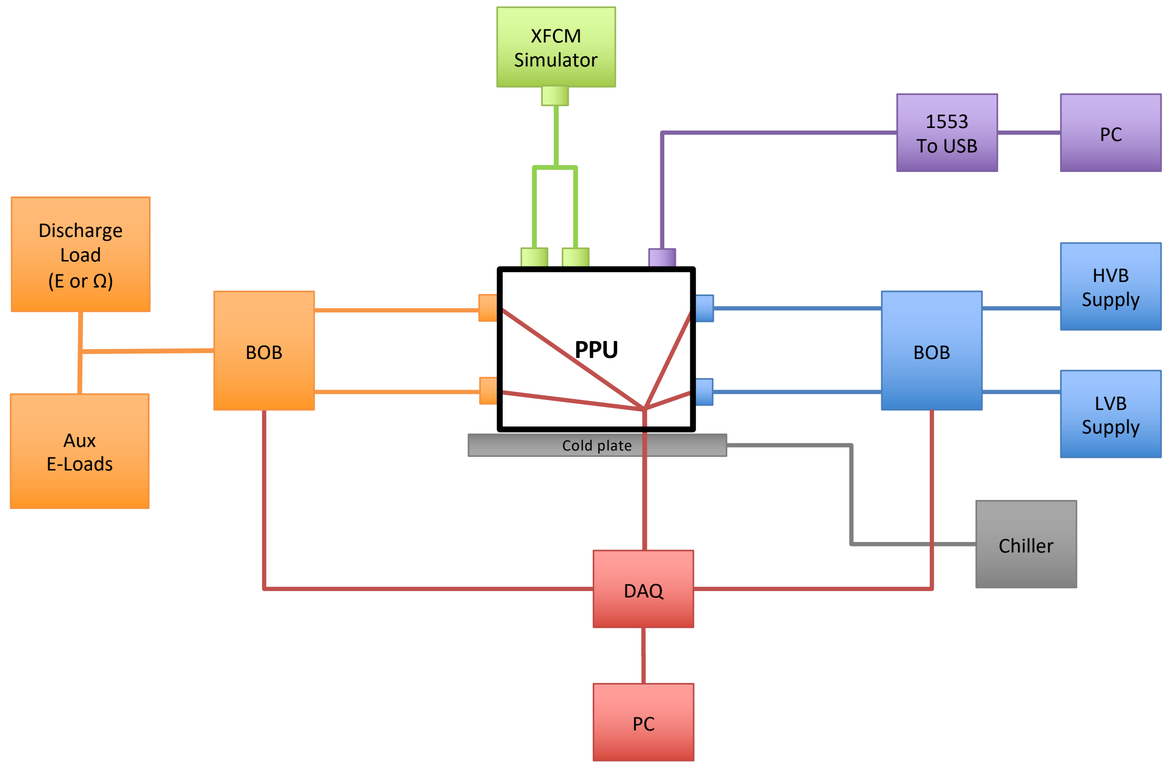
- ✓ Verify PDU PPU requirements
- ✓ Characterize performance
- ✓ Identify problems or deficiencies

Data Collection

- Isolation
- Operating range
- Ignitor
- Regulation
- Efficiency
- Telemetry
- Setpoints
- Idle power
- UV & OV
- Output faults
- Transients
- Safety interlocks
- XFCM

Requirements Verification

All tested electrical performance, functional, and isolation requirements were successfully verified



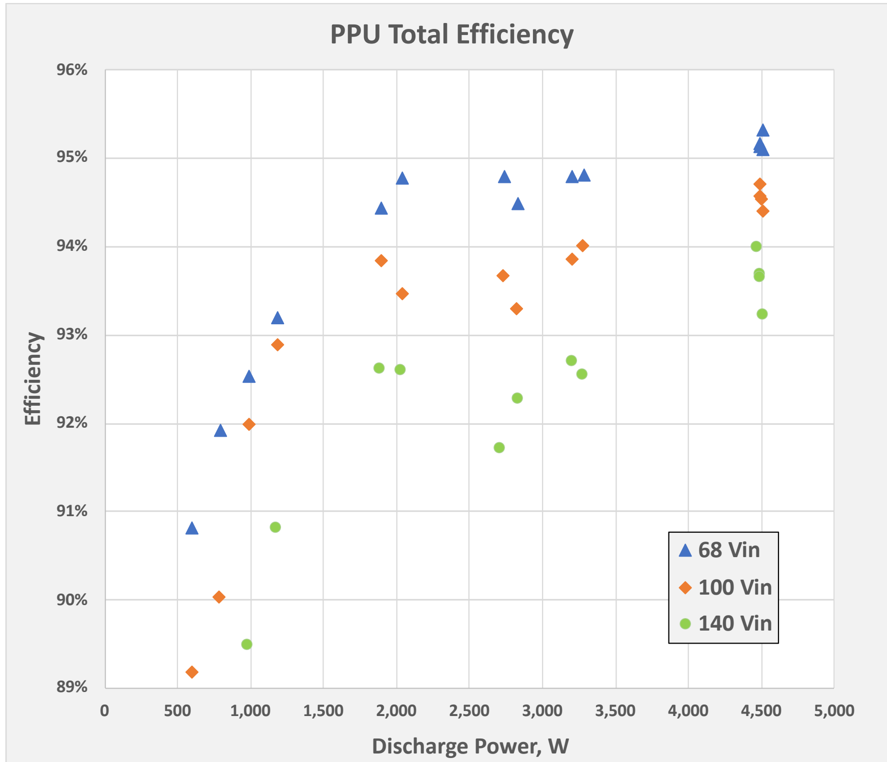
Benchtop Functional / Acceptance Testing (2/2)

PDU PPU Specifications

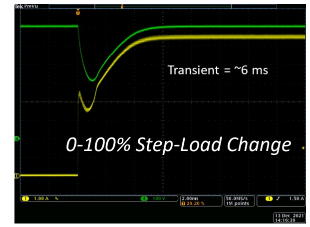
PDU PPU	Discharge	Magnets (2)	Keeper	Heater
Output Voltage	200 – 700 V	1 – 20 V	1 – 40 V	1 – 13 V
Output Current	1.4 – 15 A	1 – 7.5 A	1 – 2 A	3.5 – 21 A
Output Power Max	4.5 kW	108 W	80 W	210 W
Regulation Mode	Voltage or Current	Current	Current	Current
Output Ripple	≤ 5%			
Line/Load Regulation	≤ 2%			
Input Voltage	68 – 140 V (main) and 24 – 34V (housekeeping)			

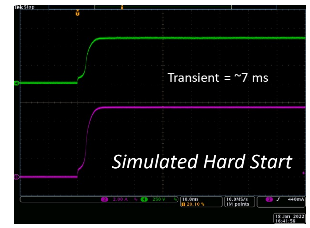
Improvements over EM PPU

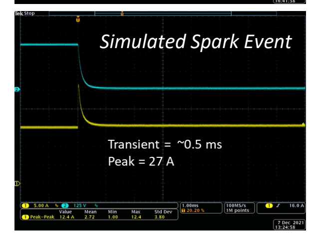
PDU PPU was successfully operated over wide input and output ranges with favorable efficiencies compared to SOA PPUs.

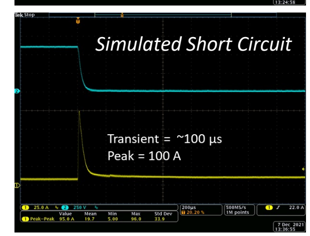


PDU PPU discharge supply displayed excellent transient behavior during load changes, simulated startups, and simulated faults.









Integrated System Tests (1/3)

CPE-NASA PPUP

IST #1 Objectives

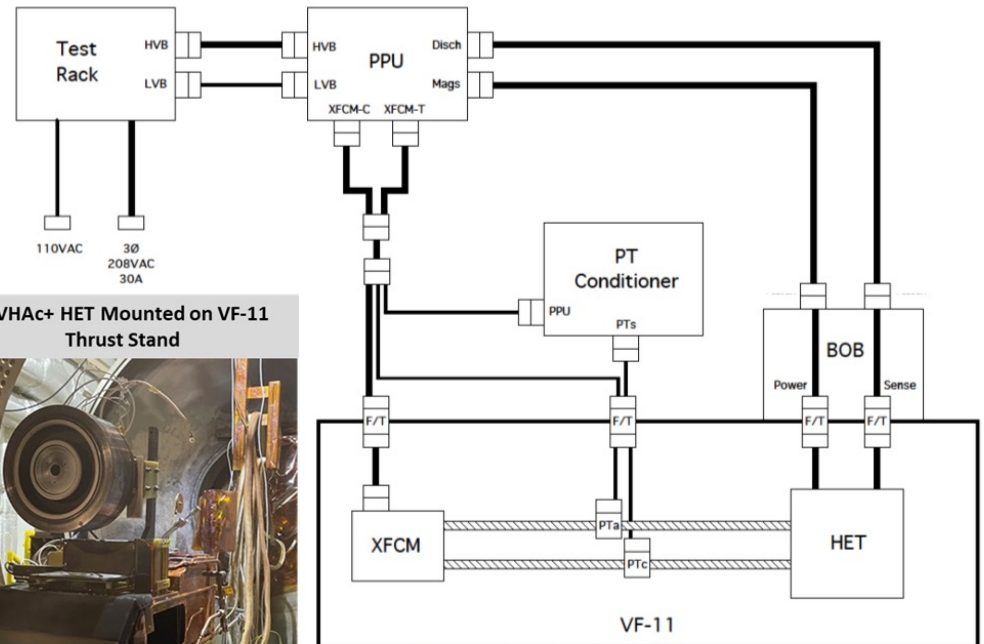
- ✓ Demonstrate PDU PPU compatibility and functionality when operated as part of an integrated 5-kW EP string
- ✓ Perform initial validation of PDU PPU algorithms
- ✓ Obtain baseline pre-environmental performance

IST #2 Objectives

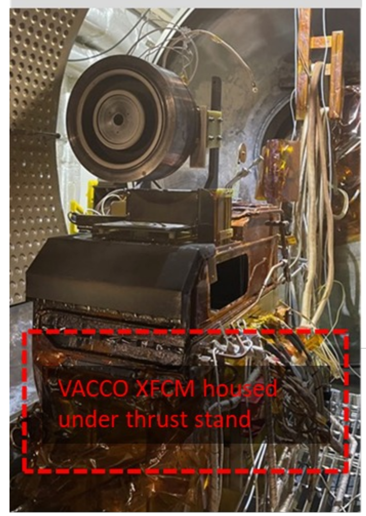
- ✓ Validate refined PDU PPU algorithms per IST #1 lessons learned

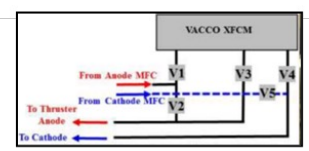
Test Plan

1. Thruster bakeout (open-loop): PPU & lab propellant feed system
2. Discharge current closed-loop: PPU & XFCM
3. Pressure / flow closed-loop: PPU & XFCM
4. Fault testing: PPU fault impacts on HET & XFCM hardware

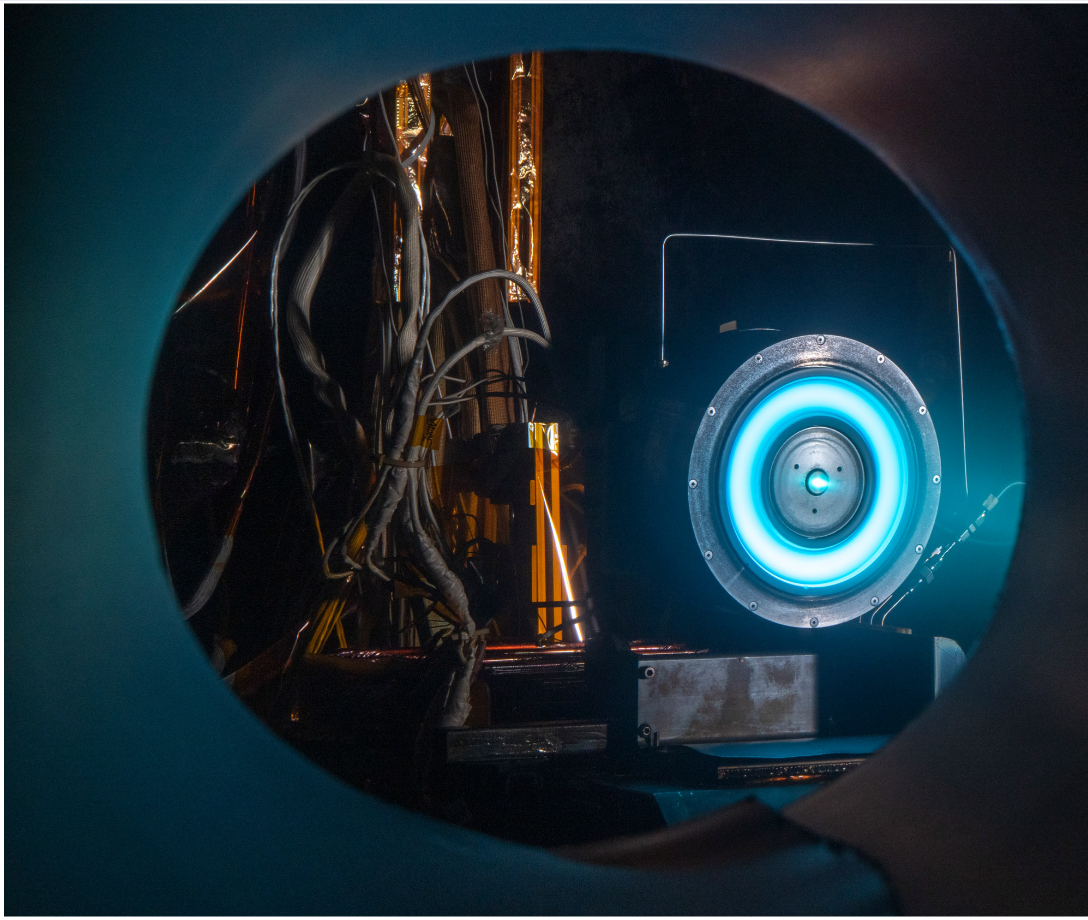


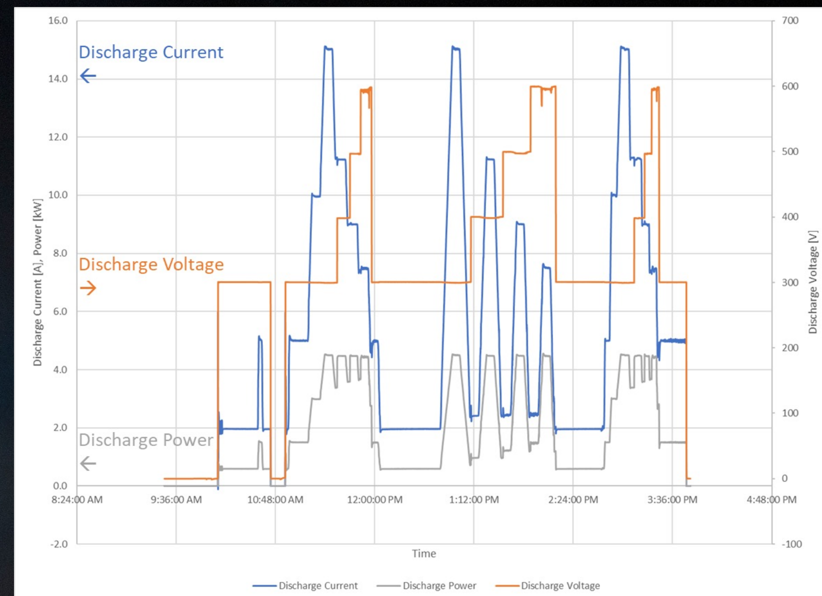
HiVHAc+ HET Mounted on VF-11 Thrust Stand





Integrated System Tests (2/3)



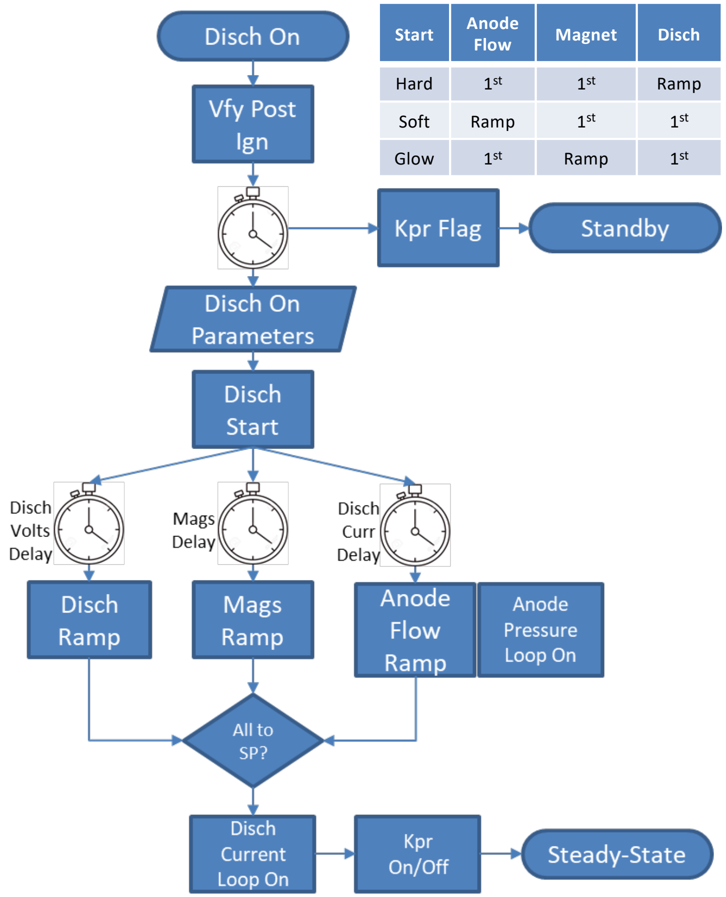


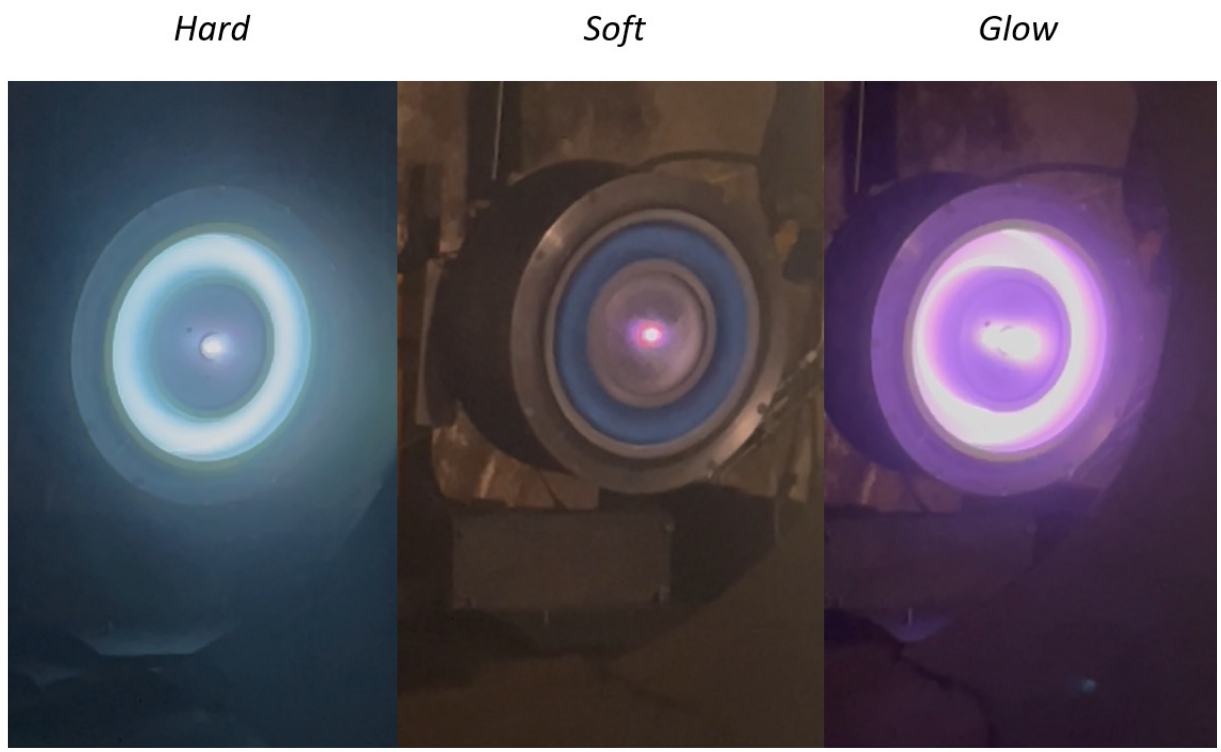
Left: HiVHAc+ operating at 4.5 kW in GRC VF-11 via the CPE PDU PPU

Above: Example test profile validating the PDU PPU algorithm refinements based on IST #1 lessons learned

Integrated System Tests (3/3)

Start	Anode Flow	Magnet	Disch
Hard	1st	1st	Ramp
Soft	Ramp	1st	1st
Glow	1st	Ramp	1st





Various thruster start modes successfully demonstrated

Approved for Public Release

EMI / EMC Test (SBIR III Support)

Test Objective

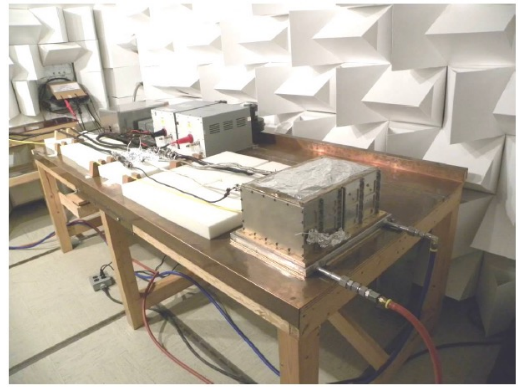
- ✓ Assess PDU PPU compliance with applicable MIL-STD-461G electromagnetic interference and compatibility requirements

Test Facility

GRC EMI Lab

Results

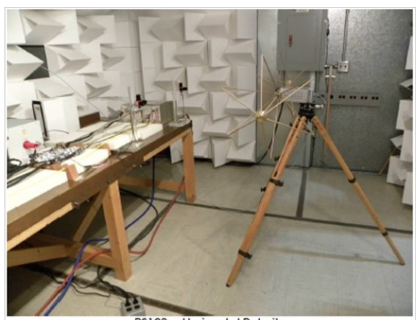
Collected conducted and radiated emissions / susceptibility measurements important for spacecraft integration



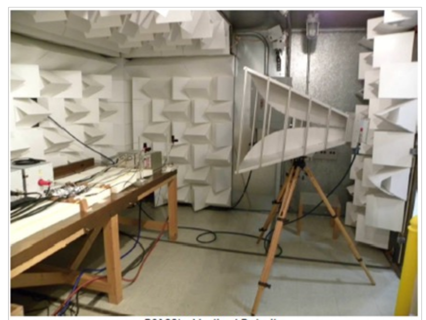
PPU in 12'x16' Anechoic Chamber

GSE in Large Chamber

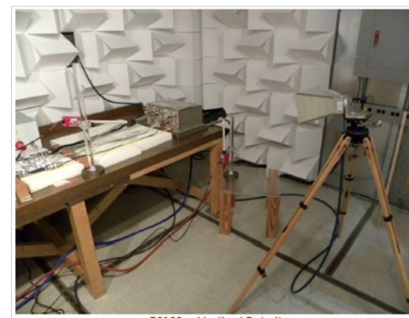
RS103a, Vertical Polarity



RS103a, Horizontal Polarity



RS103b, Vertical Polarity



RS103c, Vertical Polarity

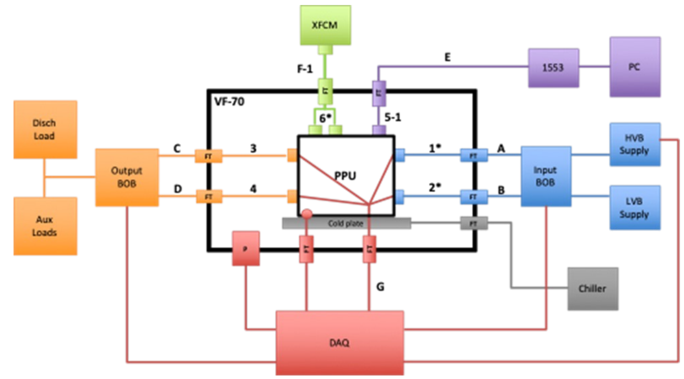
Thermal Vacuum Testing (SBIR III Support)

Test Objectives

- Demonstrate function and assess performance for TVAC cycles
- Acquire temperature data to validate PDU PPU thermal model

Key Findings

- ***August 2022***: GRC testing saw unexpectedly high thermal resistance between PPU modules and baseplate
- ***September 2022***: GRC identified insufficient fastener torquing as a primary culprit
- ***After torque adjustment***: PDU PPU was successfully operated at temperature extremes with improved thermal behavior
- ***Process improvement identified for flight***: Subcontractor workmanship issues occurred during thermocouple installation in spring 2022



Commercialization and Technology Infusion

Interest in the CPE PPU Technology

- A domestic spacecraft provider has baselined the CPE PPU for an interplanetary mission using electric propulsion
- The mission need for unregulated PPU inputs along the flight trajectory limits other commercial options
  - ❖ No commercial source exists for a complete electric propulsion system that satisfies the mission requirements

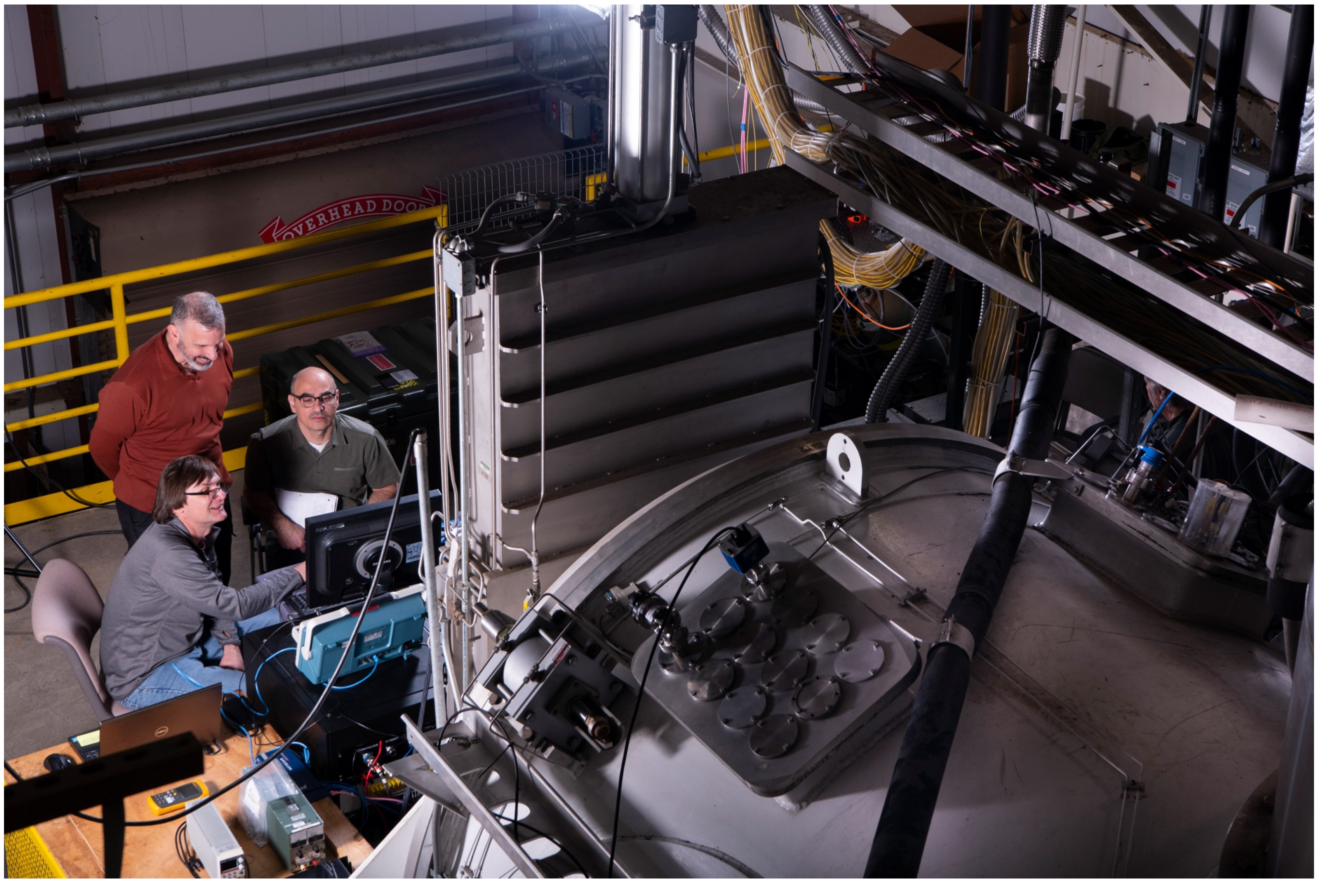
Potential Collaboration

- The spacecraft provider has formed a relationship with CPE, who recommended the involvement of NASA GRC regarding electric propulsion support
- NASA GRC is formulating a Space Act Agreement with the spacecraft provider to:
  1. Assess CPE PPU compatibility with spacecraft provider's thruster and propellant feed system options
  2. Conduct testing of the spacecraft provider's to-be integrated electric propulsion system at GRC facilities

NASA investments have advanced the CPE PPU technology sufficiently to entice a first user to take on remaining work for qualification and integration for flight!

If the effort is successful, the resulting electric propulsion system would be able to support NASA missions of interest.

Questions?



CPE-NASA PPUP